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Neil W. Ahle, Jose R. Buroni, Mark W. Sharp, and Murray P. Hamlet

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Passive rewarming of a cold water stressed foot was evaluated in 33 recovered trenchfoot (TF) patients and 15 uninjured men. Infrared images were recorded prior to immersion, immediately following and at 1 min intervals for 20 min. Individual baseline temperature (IBT) recovery was used to separate subjects into three groups designated Good and Poor Rewarming Controls (GRC and PRC) and Injured Subjects (Inj Sub). IBTs were significantly less ($p<0.01$) for Inj Sub when compared to both GRC and PRC while no difference existed between GRC and PRC. This relationship changed when slopes of and areas under the mean rewarming curves were compared. Both these criteria were significantly greater ($p<0.01$) for GRC when compared to PRC and Inj Sub while no difference was noted between PRC and Inj Sub. It could not be determined if the poor response of Inj Sub was inherent or a result of injury. We conclude that previously injured subjects and nearly 60% of a normal population may be at significant risk for cold injury.

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Infrared Thermographic Measurement of Circulatory Compromise in Trenchfoot Injured Argentine Soldiers

Neil W. Ahle, D.V.M., Jose R. Buroni, M.D.,
Mark W. Sharp, B.S., and Murray P. Hamlet, D.V.M.

From the U.S. Army Research Institute
of Environmental Medicine, Natick, MA
and
Del Hospital Militar Central
Buenos Aires, Argentina

Address for correspondence: Dr. Neil W. Ahle
Cold Research Division
U.S. Army Research Institute
of Environmental Medicine
Natick, MA 01760-5007
(508) 651-4865

THERMOGRAPHY OF TRENCHFOOT

ABSTRACT

Passive rewarming of a cold water stressed foot was evaluated in 33 recovered trenchfoot (TF) patients and 15 uninjured men. Infrared images were recorded prior to immersion, immediately following and at 1 min intervals for 20 min. Individual baseline temperature (IBT) recovery was used to separate subjects into three groups designated Good and Poor Rewarming Controls (GRC and PRC) and Injured Subjects (Inj Sub). IBTs were significantly less ($p<0.01$) for Inj Sub when compared to both GRC and PRC while no difference existed between GRC and PRC. This relationship changed when slopes of and areas under the mean rewarming curves were compared. Both these criteria were significantly greater ($p<0.01$) for GRC when compared to PRC and Inj Sub while no difference was noted between PRC and Inj Sub. It could not be determined if the poor response of Inj Sub was inherent or a result of injury. We conclude that previously injured subjects and nearly 60% of a normal population may be at significant risk for cold injury.

INDEX TERMS: Peripheral rewarming; Cold injury susceptibility; Cold water stress

Infrared Thermographic Measurement of Circulatory Compromise in Trenchfoot Injured Argentine Soldiers

Infrared Thermography (IRT) is a passive, non-invasive surface temperature measurement technique that has been used to evaluate peripheral vascular disease (9,15,18), circulatory disorders due to injury (6,17), cold induced vasodilatory response (the Hunting reaction) and other physiologic processes involving the peripheral circulatory system. Using color coded isothermic levels, a pictorial representation of the heat radiated from a surface can be produced without the introduction of artifacts seen in skin contact measuring systems. The IRT procedure has been used to measure a classical conditioning treatment performed by Raynaud's patients that was expected to alleviate their extreme cold intolerance. This work developed into a home treatment for Raynaud's disease whose efficacy was confirmed by the use of IRT (14,16). Because skin surface heat loss patterns depict underlying blood flow patterns, the increased heat emission shown in thermograms taken after initiation of a treatment regime would act as proof of the efficacy of the treatment. IRT has also been employed to test the rewarming abilities of soldiers following a cold pressor test (13). This data is being evaluated at the present time to provide insight into the possible racial differences involved in cold susceptibility. Animal work using IRT followed the progression of frostbite injury in order to predict tissue loss (8).

Veterinary Comparative Medicine Officer, Cold Research Division. United States Army Research Institute of Environmental Medicine, Natick, Massachusetts.

IRT evaluation of the long-term effect of cold injuries in man, specifically digital rewarming ability following a cold stress, has been limited primarily by the lack of sufficient numbers of subjects in one location. The large number of trenchfoot casualties and the proximity of a number of them to Buenos Aires presented an opportunity to evaluate the rewarming ability of recovered patients.

The dispute between Argentina and the United Kingdom over the Falkland Islands during the winter of 1982 resulted in several hundred nonfreezing cold injuries (NFCI) on both sides. The Falkland Islands (Islas Malvinas) are located approximately 1200 miles north of the Antarctic Circle and 500 miles northeast of Cape Horn at the tip of South America. Argentina took possession of the island group during April 1982 but forces from the United Kingdom arrived on 1 May to contest the occupation. British air and naval bombardment continued around the clock through 12 June, at times totaling as much as 14 hours in one day (11). Ground actions were continuous during this period as well with most infantry actions taking place at night.

Weather conditions in this portion of the South Atlantic during the hostilities could at best be described as abysmal. Average temperatures from April to June range from nighttime minimums of -6°C (21°F) to daily highs of 8°C (46.4°F). Average monthly rainfall for these months is 57, 64 and 54 mm respectively, roughly 2 to 2.5 inches. Humidity for the same period of time is generally 90% with fog occurring almost daily. Fighting positions were wet and generally had standing water in the bottom. One veteran involved in this study reported he had not changed his socks, nor even removed his boots, in over thirty days of combat action. The stress of constant combat under these conditions was considered responsible for nearly all of the approximately 250 NFCI's suffered by the Argentine forces during the engagement (Personal communication, Dr. (LTC) Enrique Ceballo, Del Hospital Militar Central, Buenos Aires, Argentina, February, 1988).

METHODS AND MATERIALS

Subjects: Thirty-three previously injured and fifteen uninjured control subjects were offered the opportunity to volunteer for this study by the Argentine government. Each volunteer's general health was determined prior to the test by the host nation's medical monitor. The injured subjects were clinically diagnosed as having suffered NFCI during the conflict. Seven had lower extremity tissue losses that ranged in severity from loss of a distal phalanx of one toe to a bilateral below-the-knee (BK) amputation. Seven indicated that their hands were also affected to varying degrees but only the BK amputee suffered tissue loss (surgical amputation of the distal phalanx of the right forefinger) as a result. All others had no clinical signs of NFCI or its sequellae other than subjective accounts of weight-bearing surface pain, cold sensitivity or hyperhidrosis.

Equipment: The subject's temperatures were monitored by utilizing an AGEMA TIC-8000 Infrared System (AGEMA Infrared Systems, Danderyd, Sweden) comprised of an upgraded AGEMA 782 Thermovision® infrared (IR) camera, an IBM PC/AT® computer, and the Computer Aided Thermographic System (CATS version

1.04) software package. The TIC-8000 system electronically stores digitized IR images for later retrieval, manipulation and analysis. Ambient air and water bath temperatures were measured by a Doric temperature indicator model #450-TH manufactured by Doric Scientific, San Diego, California and recorded manually as necessary.

Subject Preparation and Position: All subjects were seated quietly with shoes and socks removed for a twenty minute equilibration period prior to a baseline IR image being recorded. After equilibration the subject was seated in a hydraulic lift chair with his foot placed into a draft free, emissivity neutral enclosure under the field of view of the IR camera. The height of the chair was adjusted so that a normal seated position was attained. The camera viewed downward onto the dorsum of the foot by means of a front silvered mirror and the foot rested upon an emissivity neutral wire grid above an ice and water background. The landmark for uniform placement of the foot under the IR camera was established by using the anterior edge of the ankle at its transition onto the dorsum of the foot. This angle where vertical shin meets horizontal foot was the lower limit of the IR camera field of view. This placed the distal portion of the foot in the center field of view of the camera which minimized distortion and loss of accuracy.

Cold Water Stress Test (CWST): The foot being tested was then covered by a 3 mil disposable polyethylene boot (Edmont Poly-D #35-350, Becton Dickinson and Co., Coshocton, Ohio 43812) to prevent wetting and immersed above the ankle but below the top of the covering into a well-stirred 10±0.1°C water bath. The water bath was supplied by a Haake F3-K Refrigerated Bath & Circulator unit (Haake Buchler Instruments, Inc., 224 Saddle River Road, P.O. Box 549, Saddle Brook, New Jersy 07662) equipped with a recirculating pump. The output temperature of the Haake unit was adjusted as necessary to maintain the immersion bath at 10°C. Duration of the CWST was 10 minutes unless the individual could no longer tolerate the immersion and withdrew earlier.

Rewarming Period Image Collection: Immediately after the CWST the boot was removed, trace moisture was blotted dry with a terrycloth towel and the foot was placed under the IR camera in the manner described above. Thermal images were collected immediately after placement of the subject's foot (T=0) and then at one minute intervals until twenty minutes had elapsed (T=20). In order to minimize artifactual temperature variations subjects were cautioned not to alter the position of their foot during the image collection period.

Image Analysis: The CATS software package image analysis functions were used in the evaluation of the IR images. The colder ice/water background was subtracted from each stored image and average temperatures were determined for three specified areas: the great toe alone (Great), the other four toes as a group (Small), and all five toes as a group (All). These values were recorded and used to determine each individual's Area Under the Rewarming Curve (AURC) calculated using Simpson's Rules, and his ability to recover to his individual baseline temperature (IBT). This recovery ability was calculated by subtracting the baseline image temperature from the maximum temperature reached during the rewarming period.

RESULTS

Twenty-eight of the thirty-three injured subjects were considered during analysis of IR images. Five subjects were excluded for the following reasons: the first two subjects tested were limited to two minute CWST's in order to evaluate possible adverse physiologic effects, one subject removed his foot approximately two minutes into the CWST due to pain, one subject was a self-diagnosed patient that had never been seen nor treated previously by the Argentine medical system, and one was a bilateral BK amputee. One control subject experienced a boot leak during the CWST and was excluded due to the more severe thermal stress caused by the wetting effect.

Analysis of variance within each group (injured and control) of the Great, Small and All AURCs for individual subjects indicated that the differences between the means were not significant at the $p<0.05$ level for either group. This permitted data analysis to concentrate on the All subset which was used to separate subjects within their group based upon their ability to recover to their IBT. Of the controls, five of the fourteen either met, exceed or came within 0.3°C (mean = +0.16) of their IBT. This group was designated Good Rewarming Controls (GRC). The other eight controls ranged from 4.5 to 8.5°C (mean = -6.23) less than their IBT values and controls ranged from 4.5 to 8.5°C (mean = -6.23) less than their IBT values and were designated Poor Rewarming Controls (PRC). The injured subjects ranged from 1.6 to 8.6°C (mean = -5.24) less than their IBT values and were not separated due to their uniformly poor recovery ability. These groups are graphically depicted in Figure 1. Analysis of variance of AURCs showed the GRC group to be significantly greater ($p<0.01$) than both the PRC and injured groups. Differences between means were not significant for the PRC and injured groups of subjects.

Individual IBT values and the slopes of the mean rewarming curves were also compared between the groups. IBT values differed significantly ($p<0.01$) between the injured subjects and both the GRC and PRC groups although no difference existed between the two control groupings. There was no significant difference at the $p<0.05$ level between the slopes of the mean rewarming curves for the PRC and injured subjects groups but both differed significantly ($p<0.01$) from the GRC group.

DISCUSSION

As early as 1915 surgeons recognized that TF injured soldiers would be losses for as much as three months even in moderate cases (3). One study of 351 cases admitted to a U.S. Army medical treatment facility for TF during the winter of 1943-44 found that only 83% of recovered patients were fit enough to be returned to combat duty even after an average sixty days spent in the hospital (4). While losses of this duration are of concern to the conduct of any military operation, there is a lack of data concerning the chronic fitness of TF patients. Whayne and sustained their cold injuries in World War I were still under the care of the (Veterans') Administration. Five such patients were discharged in 1946, and four more were observed in 1949" (20). This study was not concerned with the 'relatively' short recovery phase but the long term cold sensitivity and susceptibility of a group of recovered TF patients that may necessitate continued medical support.

The comparison of the three groups of toes (Great, Small and All) statistically indicated no predominant contribution to rewarming by any of the groups. It has been the experience of these investigators while reviewing IR thermograms that the great toe (and the thumb as well) generally rewarms first, reaches a higher overall temperature, and as a result should be expected to be preferentially spared NFCI. In reality, however, the great toe is frequently cold injured and it is theorized that the more exposed position of the great toe and possible greater compression on it from footgear would account for the inconsistency. No study has been found that measured relative contributions of the various toes to the distal foot rewarming effort although several studies compare one finger (1,2,5,10,12) and one measured heat loss from all toes and the forefeet (7). The lack of any significant difference of AURC means of the toe groupings in this study effectively rules out unique status for the great toe.

Baseline temperature and mean rewarming curve slope comparisons for the three groups are considered together. No initial (baseline) difference exists between the two groups of controls although both differ significantly from the injured subject group at this point. This was the expected result and would indicate that residual effects of NFCI do exist and are exemplified in one fashion by a decreased surface temperature of the affected extremity and the decreased peripheral circulation this infers. The differences that arise over the rewarming curves is of greater significance for an uninjured population. Nearly two-thirds (9 of 14) of the control group in this study failed to rewarm following a cold stress and are statistically indistinguishable from the injured group. This would indicate their inability to vasodilate in response to a cold stress, presumably leaving a large portion of a normal population at great risk for cold injury under the appropriate conditions.

The recovered TF patients also demonstrated this inability to vasodilate and regain their IBT following a cold water stress, but in their case it was unanimous failing. One author made reference to the cold sensitivity of his patients, noting cooling to an abnormal degree, prolonged rewarming times and attacks of Raynaud's phenomenon (19) but this and any other investigator's reference to long-term effects have been anecdotal. What cannot be delineated in this study is the true cause of the poor rewarming ability. It may reflect the result of the injury; the patient's reports of cold intolerance, weight bearing surface pain and hyperhidrosis six years post injury support this conclusion. It may also reflect a subset of a normal population such as this study's PRC group that is at risk for NFCI due to an inherent rewarming incompetence. Placing these individuals in conditions favorable to NFCI could result in the large numbers of casualties seen in every conflict in cold/wet climates. Examination of Figure 1 supports this conclusion. This question could be resolved by thoroughly testing a group of subjects before subjecting them to known NFCI conditions, separating them into GRC and PRC groups and comparing the injury rates of the two groups after the exercise. This study is logistically and economicaily feasible and should be seriously considered before history (once again) repeats itself.

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Human subjects participated in these studies after giving their informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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LEGENDS FOR ILLUSTRATIONS

Fig. 1. Mean (± S.E.M.) temperatures of all toes for Good Rewarming Controls (GRC), Poor Rewarming Controls (PRC) and Injured Subjects from baseline (BL) through 20 min rewarming period. Dashed lines indicate non-recorded portion of trial during cold water immersion.

Control vs. Injured Subs

Mean Temperature of All Toes